Detection of Monochromatic Photons Between 50 and 790 MeV With a $PbWO_4$-Scintillator Array[1]

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Abstract

The performance of $PbWO_4$ as a fast and compact scintillator material for calorimetry at energies well below 1 GeV has been investigated using a collimated beam of monoenergetic photons with an energy between 50 and 790 MeV provided by the tagged photon facility of MAMI at Mainz. In continuation of previous experiments with electrons, a larger matrix of 5x5 $PbWO_4$-crystals (20x20x150-200mm^3) has been used to reconstruct the electromagnetic shower. The scintillators were selected according to their optical quality and response to low energy γ-sources. The array was operated at a stabilized temperature of T = 8°C and read-out individually by photomultiplier tubes. The achieved excellent energy resolution amounts to $\sigma/E = 1.54\%/\sqrt{E} + 0.30\%$ (E given in GeV) and has proven the applicability of $PbWO_4$ as a high quality scintillator material even at medium energies. The experimental data have been reproduced by GEANT3 simulations.

I. INTRODUCTION

$PbWO_4$ became recently well known as a fast, dense and highly radiation resistant inorganic scintillator material [1,2,3] and is therefore very suitable for the new generation of compact homogeneous calorimeters as to be constructed for the high energy detectors *CMS* or *ALICE* for LHC [4,5]. In spite of the low yield of scintillation light due to thermal quenching at room temperature, its applicability as a radiation detector at energies even far below 1 GeV has been experimentally proven in first measurements as part of an extensive test program starting with electrons between 180 and 855 MeV, respectively [6]. The energy resolution achieved with a matrix comprising 3x3 crystals (20x20 mm^2 diameter and length l = 150 mm [~ 16X_0]) amounts to $\sigma/E = 2.39\%/\sqrt{E} + 0.20\%$. The obtained time resolution $\sigma \leq 130$ ps allows photon/particle discrimination via time-of-flight technique.

In the following section the experimental set-up and the technique to measure the response function to monochromatic photons will be described. The data analysis including calibration and reconstruction of the electromagnetic shower and the lineshape of the crystal matrix will be documented in chapter III. The experimental results are discussed in comparison to GEANT3 simulations in the following chapter. The overall performance and future perspectives are given in the summary.

II. THE RESPONSE MEASUREMENT

A. The $PbWO_4$-Crystals

The used $PbWO_4$-crystals have a constant square cross-section (20x20mm^2) and a length between 150 and 201 mm corresponding to 16 to 23 X_0, respectively. The optically polished scintillators have been provided by suppliers from Belarus [7] and China [8]. All available samples have been evaluated according to their optical transparency and the scintillation yield [6]. The absolute value and the homogeneity of the optical transmission along the crystal axis were inspected within the relevant wavelength regime between 300 and 500 nm using a double beam UV-photo-spectrometer. The luminescence yield has been quantified by the mean number of photo-electrons observed in a hybrid photodiode tube (HPD) using a low energy ^{60}Co γ-source [9].

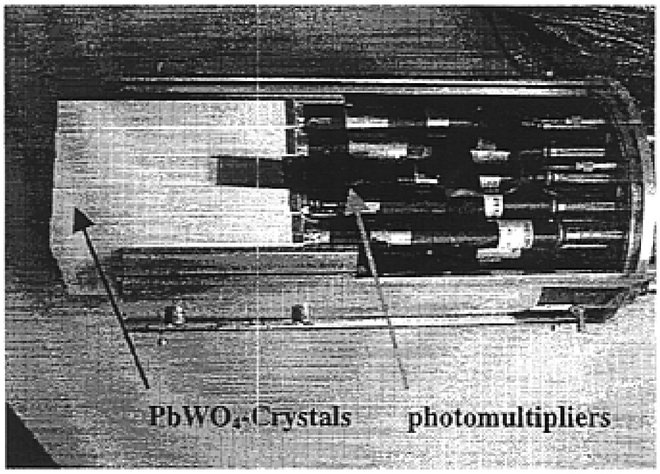

Figure 1: Experimental set-up to study the response function to photons of a 5x5 matrix of $PbWO_4$. The light-tight container, which allows operation at a stabilized temperature (T = 8^{0}C), has been opened to allow a view of the detector assembly.

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B. The Experimental Set-up

A matrix consisting of 5x5 crystals has been arranged in such a way that the quality degrades with distance from the matrix center. The crystals, individually wrapped in TEFLON foil, are coupled with optical grease (BAYSILONE 300.000) to photomultiplier tubes (Philips XP1911) and stacked into a lighttight container which can be cooled down to a well stabilized ($\Delta T < 0.1^0C$) temperature ($T = 8^0C$ in the present experiment). Fig. 1 shows the detector arrangement viewed from the top after removal of the upper cover. A plastic scintillator (5mm BC408) on the front face of the calorimeter unit serves as a charged particle veto. The crystal matrix can be moved remote controled in two dimensions perpendicular to the axis of the collimated photon beam by stepping-motors, which allows to perform the relative calibration of each detector element under beam conditions.

The individual detector signals have to be transferred via long coaxial cables (~50 m) to the data acquisition system. The photomultiplier output of each $PbWO_4$-module is digitized by means of a charge-sensitive ADC (LeCroy 2249W, integration widths IW = 140 or 220 ns) and a timing signal is deduced to determine the response time relative to the central module. Coincidences of the central calorimeter module with one of the timing signals of the chosen tagger channels are accepted under the condition that no charged particle was identified in the plastic veto detector in front. The energy and time information of each scintillator together with the timing response of the relevant tagger channels are recorded event-by-event on exabyte tape for the off-line analysis.

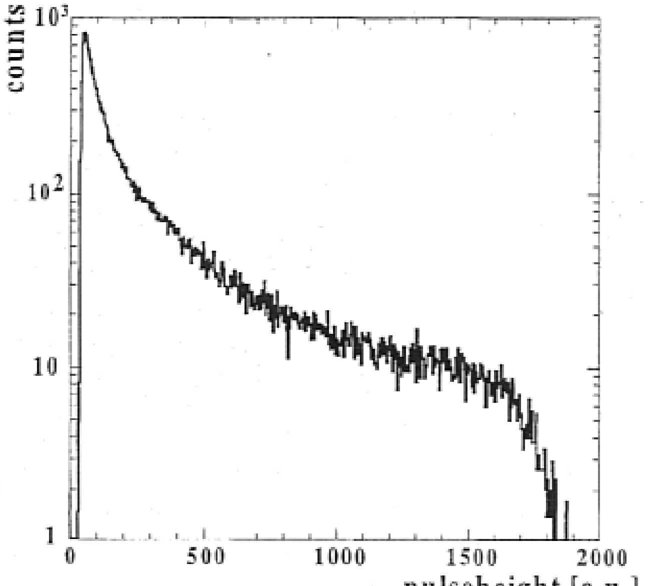

Figure 2: Response of the central $PbWO_4$-module to the full bremsstrahlung spectrum initiated by 855 MeV electrons shown in arbitrary units.

The experiment has been performed at 15 quasi-monoenergetic photon energies in the energy regime between 50 and 790 MeV. The majority of the selected energies (11) is below 200 MeV to focus on the response at lower energies. In order to minimize pile-up events, the tests have been performed at a rate < 5000 counts per second registered in the central module.

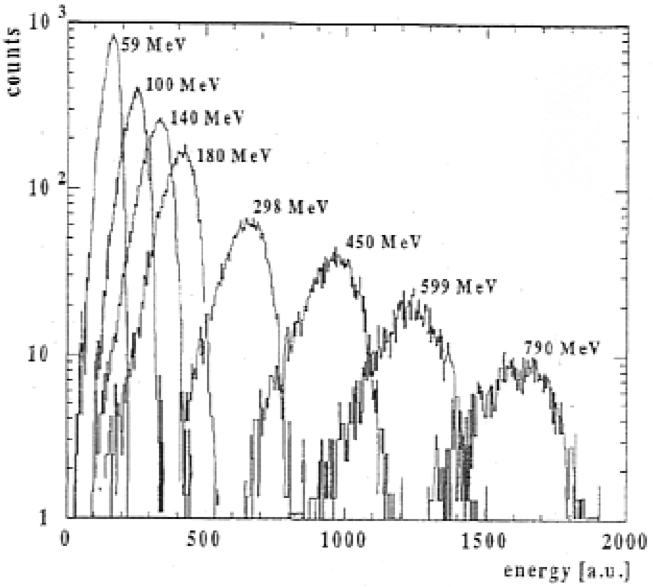

Figure 3: Response of the central detector element to eight photon energies selected by time coincidence with the corresponding electrons analyzed in the focal plane of the tagging spectrometer.

C. The Glasgow-Mainz Tagging Facility at MAMI

The quasi-monochromatic photons have been obtained by means of the high duty-factor electron accelerator MAMI at Mainz exploiting the tagging of bremsstrahlung produced by a monoenergetic cw electron beam (E_e = 855 MeV). After bremsstrahlung emission in a thin radiator the electron momenta are analyzed by the magnetic spectrometer of the Glasgow-Mainz tagger [10], requiring a time coincidence of one of the 352 electron detectors in the focal plane with the bremsstrahlung photon. The energy width per tagging channel varies between ΔE = 2.3 MeV at 50 MeV to ΔE = 1.2 MeV at 790 MeV photon energy, respectively. During the experiment 15 tagger channels have been selected to cover the full range of energies. The $PbWO_4$-array was set up at a position 13.5 m downstream from the bremsstrahlung target. A set of collimators limited the beam spot to a diameter of d = 12.8 mm at the front face of the crystals. Illustrating the applied tagging technique, the response of the central detector element to the full bremsstrahlung spectrum is given in Fig. 2. Requiring coincidence with the corresponding electrons selects discrete photon energies of a finite energy width as illustrated in Fig. 3 choosing eight tagging channels.

III. THE RESPONSE TO PHOTONS

A. Calibration and Shower Reconstruction

Each array element was illuminated in the center by the photon beam (spot size $\varnothing$ ~ 12.8 mm). The response determined for both integration gates and the pedestal of the ADC provide the relative calibration of the detector matrix to *reconstruct the total* deposited energy of the EM-shower. Figs. 4 and 5 illustrate the shower reconstruction at two extreme photon energies of E_γ = 59 and 790 MeV (IW = 220 ns), respectively.

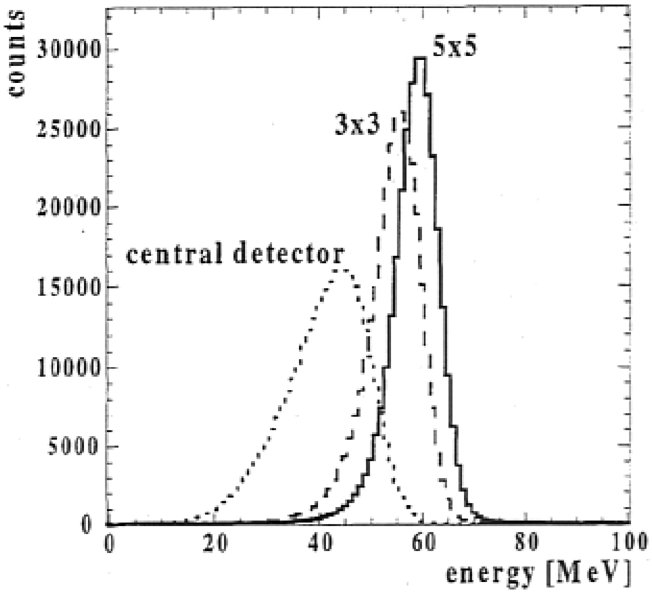

Figure 4: Response of the 5x5 $PbWO_4$ matrix to photons of 59 MeV energy. The lineshapes due to the energy deposition into the central module, the inner section of 3x3 crystals and the full array are displayed separately.

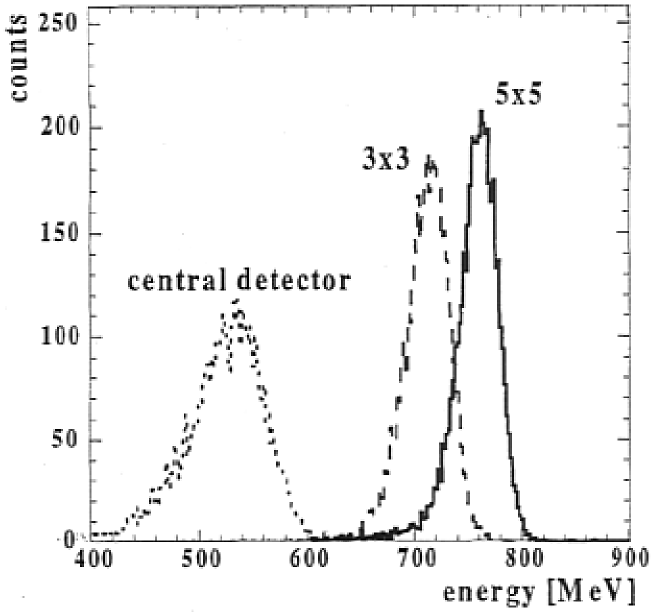

Figure 5: Response of the 5x5 $PbWO_4$ matrix to photons of 790 MeV energy. The high energy parts of the lineshapes due to the energy deposition into the central module, the inner section comprising 3x3 crystals and the full array are displayed separately to illustrate the improvement of the energy resolution.

The lineshapes obtained for the central module, the inner section comprising 3x3 crystals and the total array are shown for comparison. At both energies a fraction of ~ 70% of the energy absorbed in total is already deposited into the central module. However, adding in the amount of lateral leakage of the EM-shower leads to a significantly narrower and almost Gaussian lineshape expressed by a drastic improvement of the resolution. From the energy distribution measured with the full 5x5 matrix the excellent energy resolutions of σ/E = 6.54% (E_γ = 59 MeV) and σ/E = 2.16% (E_γ = 790 MeV) have been deduced.

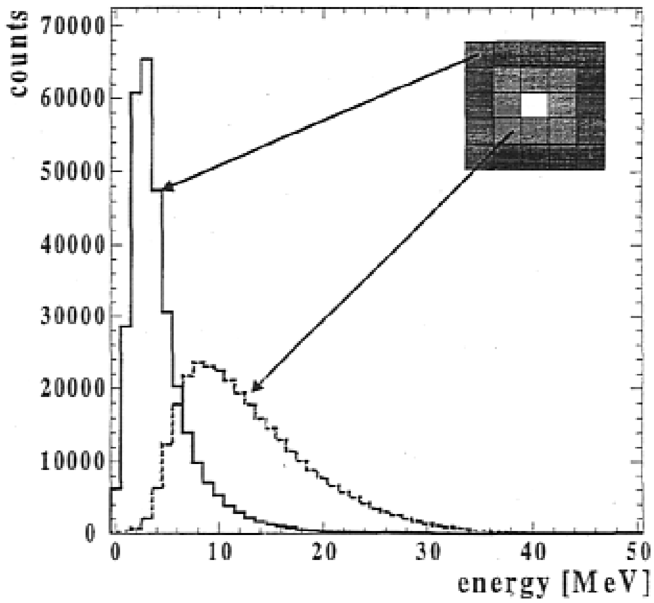

Figure 6: Distribution of the shower energy deposited into the inner and outer ring of neighbors and next-neighbors to the central crystal measured at E_γ = 59 MeV.

Figs. 6 and 7 show complementary the distributions of absolute energy deposition into the rows of neighboring and next-neighboring crystals, respectively, shown again for both photon energies. The reference for the absolute calibration has been taken from GEANT3 simulations (see next chapter). The most probable value of the energy deposited into the active scintillator volume predicted by the shower code has been related to the similar value of the experimental spectrum which contained the sum over all contributions in the individual detectors above the pedestal.

The calibration is based on the absolute value of the deposited energy. The limited volume of the 25 $PbWO_4$-crystals and the inactive reflector material in between cause a small leakage of the electromagnetic shower out of the calorimeter unit. Within the experimental uncertainties, the correlation between the measured most probable energy deposition (E_γ^{meas}) and the true incident photon energy (E_γ^{inc}) can be approximated by the linear expression $E_\gamma^{inc} = 1.031 \cdot E_\gamma^{meas}$ (IW = 220 ns) in the investigated energy regime.

B. The Energy Response

The signal shape of all used crystals show slow decay components ($\tau > 100$ ns) [6], which explains the substantial increase of the light output averaged over the array by 12% when integrating over a time width of 220 ns instead of 140 ns.

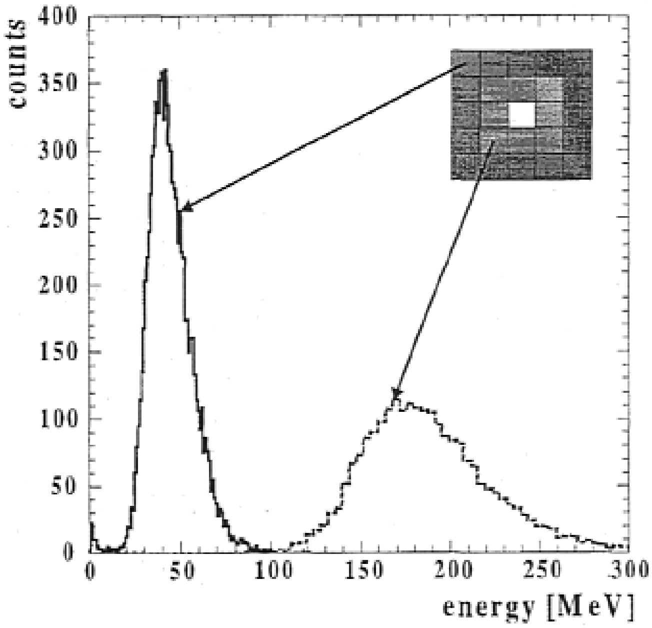

Figure 7: Distribution of the shower energy deposited into the inner and outer ring of neighbors and next-neighbors to the central crystal measured at $E_\gamma = 790$ MeV.

The energy resolution (σ/E) can be directly taken from the measured response functions (σ = FWHM/2.355) as shown in Figs. 4 and 5. The dependence on the incident energy for the 5x5 matrix can be parameterized for both integration gates according to equation (1) and (2) as

IW = 140 ns: $$\sigma / E = 1.52\% / \sqrt{E[GeV]} + 0.41\% , \quad (1)$$

IW = 220 ns: $$\sigma / E = 1.54\% / \sqrt{E[GeV]} + 0.30\% , \quad (2)$$

which corresponds to a resolution value well below $\sigma/E = 2\%$ at a photon energy of $E_\gamma = 1$ GeV. The result is only slightly affected by the increase of the width of the integration gate. However, if the active volume is restricted to a geometrically smaller matrix comprising only 3x3 crystals, the resolution values (see equation (3) and (4)) change to

IW = 140 ns: $$\sigma / E = 1.78\% / \sqrt{E[GeV]} + 0.58\% , \quad (3)$$

IW = 220 ns: $$\sigma / E = 1.69\% / \sqrt{E[GeV]} + 0.63\% , \quad (4)$$

but are still significantly superior to the parameters reported in the first measurement with electrons using a prototype assembled of not quality selected modules [6]. Fig. 8 depicts the relative resolution values as a function of the incident photon energy measured for the integration width IW = 220 ns for both geometries. The previously obtained result for electrons as well as the energy performance of the BaF_2-spectrometer TAPS (calorimeter depth – 12 X_0) are shown for comparison. In the latter case, the response function has been determined by integrating either over the total light output or the fast component only [11]. The finite incident energy width of the photons given by the chosen individual tagger channels has not been unfolded. Even at the lowest energies the correction remains within the overall experimental uncertainties and therefore has been neglected.

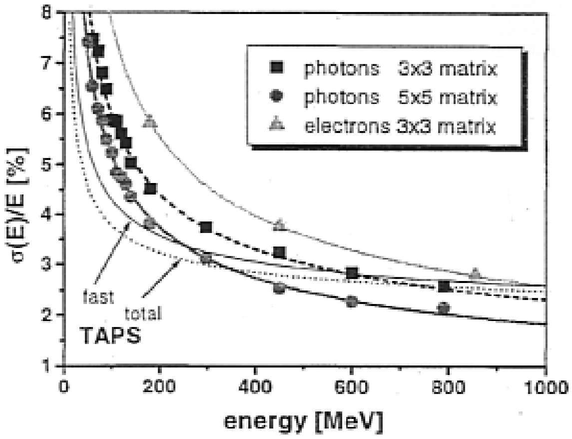

Figure 8: The experimental energy resolution of the 5x5 $PbWO_4$ crystal matrix shown as a function of the incident photon energy. The response of the 3x3 sub-unit is shown separately. The corresponding values obtained previously with electrons [6] and the performance of the BaF_2-spectrometer TAPS [11] for the fast and total scintillation yield are shown for comparison.

C. The Position and Time Response

The lateral distribution of the shower allows a more accurate determination of the position of impact of the photon than given by the granularity of the matrix. In spite of the strong shower fluctuations at incident energies below 1 GeV the impact point can be obtained from a logarithmically weighted average over those detectors that fired. An appropriate weighting has to account for the transverse profile of the EM-shower. Due to the large spot size of the collimated photon beam (Ø = 12.8 mm) and the unknown spatial distribution of the beam intensity the estimated position resolution in both dimensions of $\sigma_{x,y} \leq 5$ mm represents only an upper limit, which is consistent with previous measurements [6] using a well localized electron beam.

The timing signal provided by a constant-fraction discriminator for each matrix component has been measured relative to the central detector. Similar pulse height spectra for two coincident detector elements are achieved by positioning the beam between two adjacent modules. From the distribution of the time difference of the two modules a width of $\sigma = 590$ ps and 340 ps, respectively, has been deduced at incident photon energies of $E_\gamma = 59$ MeV and 790 MeV. The discriminator threshold corresponds to an energy deposition of ~ 1.5 MeV. No off-line correction has been applied to compensate the discriminator-walk. Assuming an identical behavior of each module the experimental time resolution per detector reduces by a factor of $\sqrt{2}$ to $\sigma = 417$ ps and 240 ps for both energies.

IV. COMPARISON TO SIMULATIONS

The EM-shower initiated by photons between 50 and 790 MeV has been simulated as mentioned before by means of the computer code GEANT3 [12]. The calculations take only into account the crystal geometry and the energy loss due to dead material such as the TEFLON reflector layer between adjacent crystals. The most probable value of the predicted deposited total energy has been used for an absolute energy calibration of the detector signals.

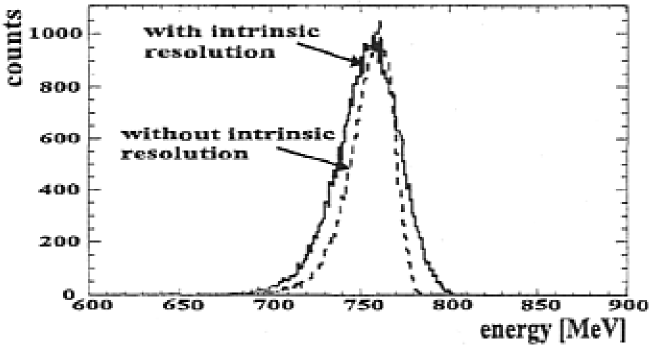

Figure 9: Simulated lineshapes of a 5x5 $PbWO_4$-matrix at an incident photon energy of 790 MeV. The response predicted by GEANT3 (dotted curve) has been folded with an empirical correction to account for the intrinsic resolution of the detector (see text for details).

As shown in Figs. 9 and 10, a good overall agreement of the lineshape can be achieved only if the calculated energy E_d, which is deposited into the individual detector module, is folded with a Gaussian of an energy-dependent FWHM, $\Delta E_d / E_d = 3.19\% / \sqrt[4]{E_d}$ (E_d given in GeV). This empirical correction accounts for resolution losses in the real detector due to photon statistics, electronic noise and the inefficient collection of the scintillation light, which is not explicitely incorporated into the simulation. Fig. 10 illustrates the achieved reproduction of the lineshape in a comparison to the high energy part of the experimental spectrum.

V. DISCUSSION AND SUMMARY

The response to quasi-monochromatic photons has been measured with an array of large $PbWO_4$ crystals of depth > 16 X_0 read-out by photomultiplier tubes. The reconstruction of the EM-shower delivers good energy, position and time resolutions. In spite of the low scintillation yield of $PbWO_4$, excellent resolution values < 7.5% have been achieved for the first time even at a photon energy as low as 50 MeV. The crystals have been operated at a stabilized temperature ($T = 8^0C$) and the signal shape was integrated over a 220 ns wide gate. At an energy of 1 GeV the relative resolution drops well below $\sigma/E = 2\%$. The comparison to the specifications of the TAPS spectrometer shows that above $E_\gamma \sim 400$ MeV the reduced shower leakage of the $PbWO_4$-unit can compensate for the low luminescence yield, in particular compared to BaF_2. As a conclusion, a more homogeneous crystal performance, a further enhanced output of the scintillation light and an improved light collection give future opportunities to bring the resolution values even further down.

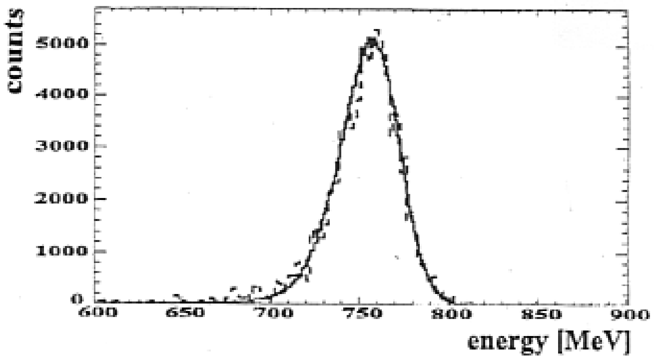

Figure 10: Comparison of the simulated and experimental lineshape (dotted histogramm) of a 5x5 $PbWO_4$-matrix at an incident photon energy of 790 MeV. The GEANT3 prediction has been folded with an empirical correction to account for the resolution losses in a real detector array (see text for details).

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